

Classification of light curves of the black hole candidate GRS 1915+105

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Abstract The black hole candidate GRS 1915+105 exhibits a rich variety of variability. Assuming that the earlier paradigm of black hole accretion which includes a shock is applicable for this system as well, one can classify these variabilities into four classes. We present light curves of these classes and discuss the basis of our classification.

Keywords Black holes, X-ray sources, outflows.

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1. Introduction

GRS 1915+105 is a stellar mass black hole candidate in our galaxy which exhibits very rich time-variability. It is termed as a micro-quasar since it has most of the features of a quasar, such as a superluminal jet which moves at a speed of 98 percent of the velocity of light [1,2]. Morgan *et al* [3] pointed out that the source is sometimes in low-hard state, but in other times it goes to flare state with considerable variations in amplitude and quasi-periodic oscillation frequency. They showed that there are several time-scales of quasi periodic oscillations (QPO) ranging from 67 Hz to 0.01 Hz (see, also, Munro *et al* [4]). Recently, it has been pointed out [5–7] that there is a distinct correlation between the oscillation frequency and the duration of oscillation. This correlation has been explained by invoking repeated formation and cooling of the wind generated from the centrifugal pressure dominated boundary layer (CENBOL) of the black hole [5,7]. (Wind production from accretion flows are also discussed in Das and Chakrabarti [8]). Several types of oscillations have been plotted in Manickam and Chakrabarti [6].

Given that accretion disk models around black holes are pretty well understood [9,10], and variation of accretion rates, out flow rates, shock locations, cooling processes *etc.*, can make spectral change dramatically, it is not perplexing as to why GRS 1915+105 exhibits such a rich variety of oscillations. It was already pointed out [11,12] that oscillation of shock waves could be responsible for the QPO. Later, this model was proven to be correct [6,7] where it was shown

that soft X-rays (0–4 keV) emitted from the pre-shock region, do not participate in QPOs and only hard X-rays (4–13 keV) show quasi-periodic behaviour.

In this *Rapid Communication*, we present a classification of the light curves based on our understanding of the black hole accretion process according to which not only Keplerian matter, but also substantial amount of sub-Keplerian matter accretes into a black hole and the sub-Keplerian flow often produces stationary or non-stationary shocks. We find that although there are several types of light curves, the number of classes could be as few as four. In our picture, the post-shock flow is heated up and puffed up and intercepts soft photons from the pre-shock region. In the pre-shock region, Keplerian disk is situated in the equatorial plane and is flanked by poorly emitting sub-Keplerian matter above and below. The post-shock flow produces winds and outflows, rates of which depend on the spectral states of the black hole [13]. In the hard states, there is a continuous outflow at a smaller rate, while in the soft states, no outflow is produced. When the compression ratio of the shock is intermediate, outflow rate is maximum and flares and variabilities are prominent.

That the outflows are originated from CENBOL has now been confirmed by several workers. Mirabel and Rodriguez [2] and Dhawan *et al* [14] found evidence of IR flares and radio flares which are directly correlated with the X-rays produced by inverse-Comptonization at the base of the jet. Similarly, Fender [15] concluded that the base of the jet is the same place where X-rays are originated. Junor *et al* [16]

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found that jets in M87 must be originated within a few tens of Schwarzschild radii.

If our paradigm as described above is correct, and the X-ray variability is primarily due to variability of the hard X-rays, then it is conceivable that the light curves could be classified according to the photon counts from pre- and post-shock flows. This is precisely what we do. In the next Section, we briefly present the theory of photon emission from the pre- and post-shock flows. In Section 3, we plot the light curves and the softness ratios and classify the light curves into four classes. Finally, in Section 4, we draw our conclusions.

2. Brief theory of photon emission from an accretion disk around black holes

For a Keplerian disk, the surface flux of soft X-rays emitted is given by [17],

$$F = 5 \times 10^{26} \left| \frac{\dot{M}_{17}}{M^2} \right| r^{-3} I \text{ erg cm}^{-2} \text{ sec}^{-1}. \quad (1)$$

Here, M is the mass of the black hole, measured in units of M_\odot , the mass of the sun, \dot{M}_{17} is the mass accretion rate of the Keplerian component in units of 10^{17} gms/sec, r is the distance from the black holes measured in units of $r_g = GM_{BH}/c^2$ (M_{BH} is the mass of the black hole, G is the gravitational constant, c is the velocity of light all measured in cgs units), $I = 1 - (6/r)^{1/2}$. For an optically thick flow, the black body radiation that is emitted locally is that of temperature

$$T_e(r) = [4F(r)/a]^{1/4} \\ = 5 \times 10^7 M^{-1/2} (\dot{M}_{17})^{1/4} r^{-3/4} I^{1/4} K. \quad (2)$$

Here a is the radiation constant. Close to $r = 20$ and for $M = 10$, the temperature is roughly 1.4 keV which corresponds to soft X-ray radiation. A part of this radiation is intercepted by the post-shock region [18] and is re-emitted after being energized by inverse-Comptonization process. If the accretion rate is very small, inverse-Comptonization still leaves the post-shock region hotter and hard radiation as well as winds are produced. If both the Coulomb heating and inverse-Comptonization are important, the electrons are roughly $(m_p/m_e)^{1/2}$ times cooler than the protons: $T_e \sim (m_e/m_p)^{1/2} T_p$. In the post-shock region: $T_p \sim 10^{11}$ K and $T_e \sim 2 \times 10^9$ K. Power-law radiation emitted by successive scattering can produce radiation starting from 2 to 200 keV or more. Even higher energy radiations can be emitted by synchrotron processes.

When Keplerian accretion rate is very high, they cool the post-shock electrons completely and the shock vanishes. The post-shock region also resembles like an optically thick Keplerian flow, but the inner edge of the disk ($r < 6$) produces hard radiation due to bulk-motion Comptonization [18].

In the event of oscillating shocks, the winds produced may not leave the system and stalled jets are produced.

Matter in the subsonic region of the wind falls back to equatorial disk as soon as it is cooled due to inverse-Comptonization. This periodicity gives an expression for the duration of QPOs which is found to be well correlated with the QPO frequency [5,7]. Various types of QPOs which are observed could be due to variations of accretion rates in Keplerian and sub-Keplerian components and shock location (which is determined by the specific energy and specific angular momentum of the inflow).

3. Classification of light curves

Figure 1 shows possible variations of the light curves of GRS 1915+105 as observed by the RXTE satellite. Twelve panels are marked. Panels 3 and 6 have more than one light curve (separated by dashed line), as they are similar but with subtle

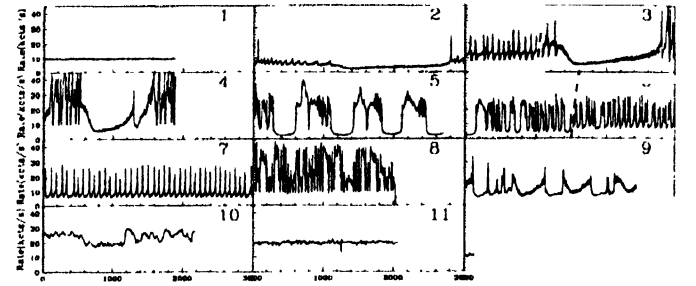


Figure 1. All possible light curves of the black hole candidate GRS 1915+105. Along X-axis is time in seconds and along Y-axis is photon counts in units of 10^4 . In Panels 3 and 6, two days of curves differing slightly, have been shown.

difference. Along X-axis is the time elapsed in seconds since the beginning of the observation. Spectral analysis of the 1st panel suggests that it is purely in hard state. There is a prominent QPO whose frequency may change from time to time and photon count number may also change significantly. Final three panels (10–12) contain light curves of those days on which spectral states are soft. There are no QPOs in these days. Spectral fits indicate high temperature and high photon spectral index. The ninth panel contains a light curve where two semi-soft spectra with different photon counts are seen. Count rate varies very significantly. In the remaining seven panels (2–8) photons jump in between two distinct states, one with a low photon count (off state) and the other with a high photon count (on state). These twelve types have been designated as χ , α , ν , β , λ , κ , ρ , μ , θ , δ , γ and ϕ respectively by Belloni *et al* [19]. They also plot hardness ratios of these cases where (B/A) vs (C/A) were depicted. Here, A , B , C are photon counts in (0–5) keV, (5–12) keV and (12–60) keV ranges. These hardness ratios show various well known features such as Atoll, Z-type *etc.* very similar to what was observed in neutron star candidates.

According to the paradigm of Keplerian/sub-Keplerian flow, the following should be happening close to a black hole [18]: Keplerian flow moves in the equatorial plane while sub-Keplerian flow moves above and below the plane. The Keplerian flow itself becomes sub-Keplerian close to the

black hole. The combined sub-Keplerian flow then continues to move towards the black hole and forms a standing or oscillating shock if the specific energy is positive. Otherwise, the combined flow forms a smaller centrifugal barrier dominated region and passes through the inner sonic point. The post-shock region reprocesses soft photons from the Keplerian disk and emits essentially hard radiation provided Keplerian accretion rate is small enough, otherwise, the post-shock region also cools down [18]. While hot, the post-shock region produces winds. If the outflow rate is large enough, it may intercept soft and hard photons and re-process. If the outflow is 'failed', namely, do not pass beyond the sonic point due to various factors such as cooling down by inverse Comptonization [5,7], it may fall back onto the post-shock region and the object may behave as if the accretion rate had gone up. Most of the on/off transitions can be easily interpreted in this way.

If the pre-shock flow is indeed the source of the soft photons, photons originating in (0–3) keV range should be roughly proportional to the accretion rate in the cool component (basically Keplerian). Thus, photon number may show time variation (due to periodic change in the 'accretion rate'). However, no QPO should be seen. Chakrabarti and Manickam [7] demonstrated this. This harder photons ($E > 3$ keV) would usually come from the post-shock flow. Since spectra intersect at around 17 keV, and for $E > 17$ keV, photon number is not large, we make our choice of A , B and C to be those in ranges (0–3) keV, (3–17) keV and (17–60) keV respectively. According to our paradigm, roughly speaking, A , B and C should be proportional to each other, (since B and C produced by interception of soft photons. Of course, soft X-ray absorption makes matter more complex.) and whenever hardness or softness ratios are plotted basically straight lines are expected, instead of Atoll, Banana and Z shapes which do not give any insight into the problem. Figure 2 shows twelve panels (in the same sequence as in Figure 1) where B/C is plotted along X-axis and A/C is plotted along the Y-axis. We call this a 'softness ratio' diagram. In some of the panels (No. 2–4, 6–8), the ratio is zoomed in to show details. One observes that panels (9–12), which are for soft or nearly soft spectra, the plots are roughly linear and the lower-left end starts at sufficiently large number compared to the other panels. Power density plots do not show evidence of QPO in these types of light curves. Light curves of all other panels show QPO.

The softness diagrams could be classified into the followings :

1. HARD Class (H) : Panel 1
2. SOFT Class (S) : Panels 10–12
3. SEMI-SOFT Class (SS) : Panel 9
4. INTERMEDIATE Class (I) : Panels 2–8

Each of these classes have subclasses in terms of variation in light curves and softness ratios. For instance, in Class H, counts and QPO frequencies vary and the spot mark in

Panel 1 moves around. In Class S, the slopes and the co-ordinates of the lower-left point varies, but the general nature is similar (Panels 10–12). In Class I, the duration of the off

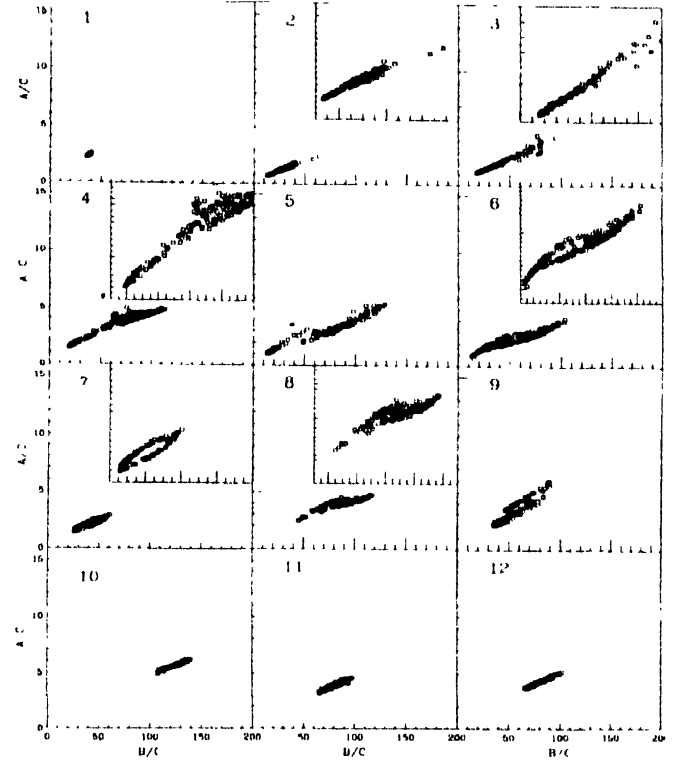


Figure 2. Softness Ratio A/C vs B/C is plotted for all the 12 panels shown in Figure 1. A , B , and C are photon counts within intervals (0–3) keV, (3–17) keV and (17–60) keV respectively. Panel 1 belongs to Class-H, Panel 9 belongs to Class-SS. Panels (10–12) belong to Class-S and the rest belong to Class-I. See, text for details.

and the on state may vary systematically from one sub-class to the next. The duration of the on-state (high count) may be almost zero (Panel 7). At the same time, the co-ordinate of the lower left corner point in the softness ratio diagram varies systematically. As discussed in Section 2 [eq.(1)], soft photon count A is directly related to the accretion rate in the Keplerian disk and hard photon count B is related to the degree of interception, and sum of Keplerian and sub-Keplerian accretion rate (total matter in the post-shock region). Thus, different members of this sub-class are directly related to these accretion rates. The common ground is that the duration of the off-states in all of these sub-classes are found to obey the correlation with QPO frequency [7]. The process of generating light curves purely from theoretical consideration is more involved (as feedback and other non-linear processes are present) and would be reported in future.

4. Concluding remarks

We have presented all possible types of light curves and divided them into four classes according to the nature of light curves and the softness ratios. We find that the black hole candidate GRS 1915+105 stays most of the time in Class H

state (which has QPO), while touring around other classes (only off states of which have QPOs), depending on the accretion rates in the Keplerian and sub-Keplerian flows. In Class S, the black hole is in soft state and no QPO is observed. Our simplified classification is based on the black hole accretion paradigm that explains the spectral state transitions as well as QPOs. In future, detailed theoretical modeling would be presented.

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